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Numerical analysis on the current-sharing temperature of LTS/HTS hybrid conductor

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The research of LTS/HTS hybrid conductor is a more recent topic in superconducting domain, and the current-sharing temperature is a key parameter to identify the characteristic of superconducting material. In this paper, based on the power-law model, the current-sharing temperatures for LTS and HTS were calculated respectively, and the calculated results have a good agreement with the existing equation results. The current-sharing temperature of a LTS/HTS hybrid superconducting conductor was numerically calculated. The calculated result of hybrid conductor shows that its current-sharing temperature can increase at least 0.2 K compared with typical LTS conductor with the same normalized transport current, so that the stability of this hybrid conductor is better than typical LTS supercondutor. It indicates that this LTS/HTS hybrid conductor as the substitutes of low-temperature superconductor, will have a wide application prospect and talent commercial value.

current-sharing temperature, hybrid conductor, stability

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To enhance the performance of conventional composite superconductors with large current capacity, a new LTS/HTS hybrid in which HTS is used as a part stabilizer in place of low-resistivity metals, was proposed [1,2]. The performance of every conductor is expressed in terms of current-sharing temperature (T_{CS}), which is the key design parameter and the main object of the qualification tests for the ITER, LHD conductors [3]. However current-sharing temperature has not well been studied on the LTS/HTS hybrid conductor.

In this paper, the current-sharing temperature of LTS/HTS hybrid conductor, consisting of NbTi/Cu with Bi2223/Ag, is numerically calculated based on the power-law model. The calculated current-sharing temperature results of LTS and HTS have been compared with the existing equation results. This paper will provide reference for cryogenic refrigerating and cool conducting technology especially without liquid helium.

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1 Model

This kind of LTS/HTS hybrid conductor consists of soldering LTS wire and HTS tape together or by directly winding several LTS wires and HTS tapes together in parallel mode. The LTS (NbTi/Cu) conductor stabilized with two HTS (Bi2223/Ag) tapes is shown in Figure 1.

Assume that the length of the hybrid conductor in Figure 1 is infinite and the magnetic field is uniform; it is approximately reasonable to neglect the current distribution effects induced by the joints and the couple current effect. We use the model which has been partially tested by experiment [4], where the LTS/HTS hybrid conductor can be considered to be approximately parallel circuit consisting of LTS, HTS, and metal matrix, shown in Figure 2.

As for cooling system and conduction cooled system without liquid helium, adiabatic condition can be approximately adopted. I_T is the total transport current of hybrid conductor; I_H, I_L, and I_M are the transport currents through

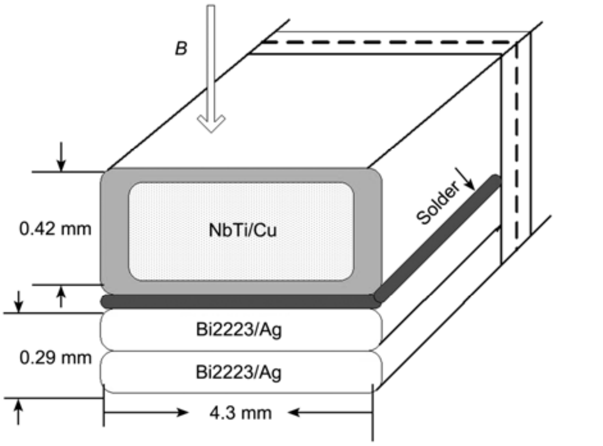

Figure 1 Schematic view of LTS/HTS hybrid conductor with combination of NbTi/Cu and Bi2223/Ag conductors and solders under the magnetic field B=6 T (in order to make the critical current of HTS comparable as possible as the LTS, two commercial HTS tapes are selected in simulation).

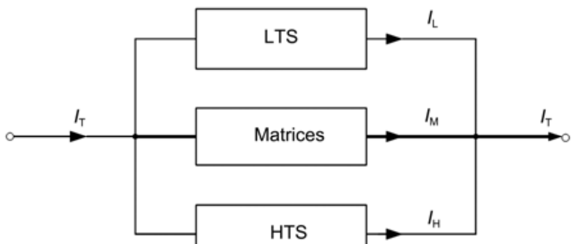

Figure 2 Equivalent parallel circuit of LTS/HTS hybrid conductor.

HTS, LTS, and matrices, respectively. In adiabatic condition, according to the power law model, the above parameters satisfy the following equations [4]:

$$\begin{cases} I_T = I_H + I_L + I_M, \\ \left(\dfrac{I_H}{I_{CH}}\right)^{n_H} = \left(\dfrac{I_L}{I_{CL}}\right)^{n_L}, \\ \left(\dfrac{I_H}{I_{CH}}\right)^{15} \times 10^{-4} = \dfrac{\rho_{avg}}{S_M} I_M, \end{cases} \quad (1)$$

where ρ_{avg} is the effective resistivity, and S_M is the cross-sections of matrices. I_{CH} and I_{CL} are the critical current for HTS and LTS respectively; n_H and n_L are the n-value of the power-law for HTS and LTS respectively. The estimation of ρ_{avg} is given by

$$\frac{1}{\rho_{avg}} = \sum_{i=1}^{n} \frac{f_i}{\rho_i}, \quad (2)$$

where f_i and ρ_i are volumetric ratio and resistivity of the i-th components in matrices except for LTS and HTS. Because the resistivity of superconductors is at least one order of magnitude more than the metal conductor, it is reasonable to neglect.

The critical current of the hybrid conductor is defined as

$$I_C(T) = I_{CH}(T) + I_{CL}(T). \quad (3)$$

Under magnetic field of 6 T, dependence of critical currents of NbTi on temperature can be approximately described by Morgan equation

$$I_{CL}(T) = 959.27\{1 - 1.195[0.315319(T-4.2) + 0.01528(T-4.2)^2 - 0.00161(T-4.2)^3]\}, \quad (4)$$

and the relation of critical current with temperature in two Bi2223/Ag tapes is approximately described by

$$I_{CH}(T) = I_C(0)\left(1 - \frac{T}{T_C}\right)^{1.4}, \quad (5)$$

where $I_C(0)$=620 A, T_C=110 K.

For the sake of convenience, the normalized transport current $\alpha = I_T/I_C$ is defined and used thereafter.

2 Results and discussion

Usually there is field E_M along conductor length. Current-sharing temperature is commonly defined as the temperature at which the voltage along the conductor reaches a threshold value defined by the critical electric field of 0.1 μV/cm [5,6]. By solving above equations numerically, the I_L, I_H and I_M are obtained. According to $E_M = I_M^2 \rho_{avg}/(I_T S_M)$ [7], then the field along conductor can be figured out (n_H=15, n_L=25 are used in all the following calculations).

Critical electric fields of LTS, LTS/HTS hybrid, and HTS conductors varied with temperature at $\alpha = 0.7$ is shown in Figure 3. It shows that the T_{CS} for hybrid conductor is between LTS and HTS, and with 0.6 K larger than LTS when the normalized transport current $\alpha = 0.7$.

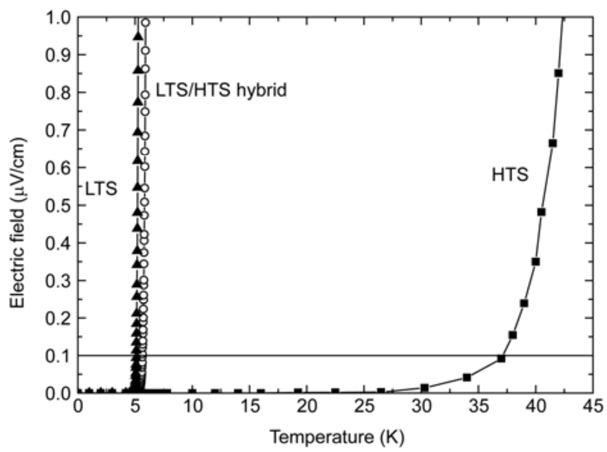

Figure 3 Critical electric fields of LTS, LTS/HTS hybrid, and HTS conductors vs. temperature, normalized transport current α=0.7 is used. The 0.1 μV/cm criterion is represented by the solid line, and TCS of LTS, LTS/HTS hybrid, and HTS conductors are 5.0, 5.6, and 37.1 K respectively.

Figure 4 shows T_{CS} comparison of LTS, LTS/HTS hybrid, and HTS conductors. It shows that T_{CS} for LTS/HTS hybrid are between LTS and HTS. While the normalized transport current $\alpha < 0.4$, T_{CS} for hybrid conductor approaches to HTS one; while $\alpha > 0.4$, it approaches to LTS one and with a few K larger than LTS. There is a turning point at about $\alpha = 0.4$, because the total transport current at this point reaches the critical current of the hybrid's HTS part and leads to this part's quench. Thus, while $\alpha > 0.4$, the current-sharing temperature of hybrid conductor is close to the typical LTS and with at least 0.2 K larger than that of LTS at the same circumstance (see Table 1).

T_{CS} can also be estimated by [8]

$$T_{CS} = T_C - \frac{I_{op}}{I_C\left(T_{op}\right)}\left(T_C - T_{op}\right), \tag{6}$$

where T_{op} and T_C are operating temperature and critical temperature respectively; I_{op} and $I_C(T_{op})$ are current and critical current at operating temperature respectively. Figure 5 shows the T_{CS} comparisons of the numerically calculated result and the equation result for LTS and HTS separately. The results show that the calculated result accords with the equation result.

3 Conclusions

The current-sharing temperature of LTS/HTS hybrid conductor in which high-temperature superconductor is used as stabilizers has been numerically investigated. The result shows that the T_{CS} of this hybrid conductor is between typical LTS and HTS ones. When the total transport current of hybrid conductor is over 40% of its critical current, its current-sharing temperature will be more close to typical LTS and with at least 0.2 K larger than that of LTS with the same normalized transport current. The LTS/HTS hybrid conductor, as a possible substitute material on LTS with pure aluminum, is to work in the low temperature like LTS. For large cooling and conducting cooled system without liquid helium, the temperature reduction of ~mK means large numbers of energy consumption in this extremely low temperature. Moreover, the working temperature range for these systems without liquid helium is very small, usually within several hundreds of mK, so the superconducting magnets

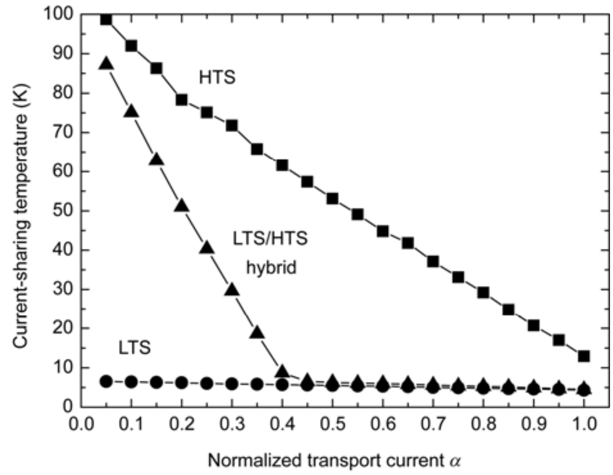

Figure 4 Calculated T_{CS} comparison for LTS, LTS/HTS hybrid, and HTS, conductors.

Table 1 Comparison of current-sharing temperature for LTS and LTS/HTS hybrid conductors

Normalized transport current α	LTS T_{CS} (K)	LTS/HTS hybrid conductor T_{CS} (K)
0.1	6.4	75.1
0.2	6.2	51.0
0.3	5.9	29.6
0.4	5.7	8.7
0.5	5.6	6.3
0.6	5.3	6.0
0.7	5.0	5.6
0.8	4.8	5.3
0.9	4.6	4.9
1.0	4.3	4.5

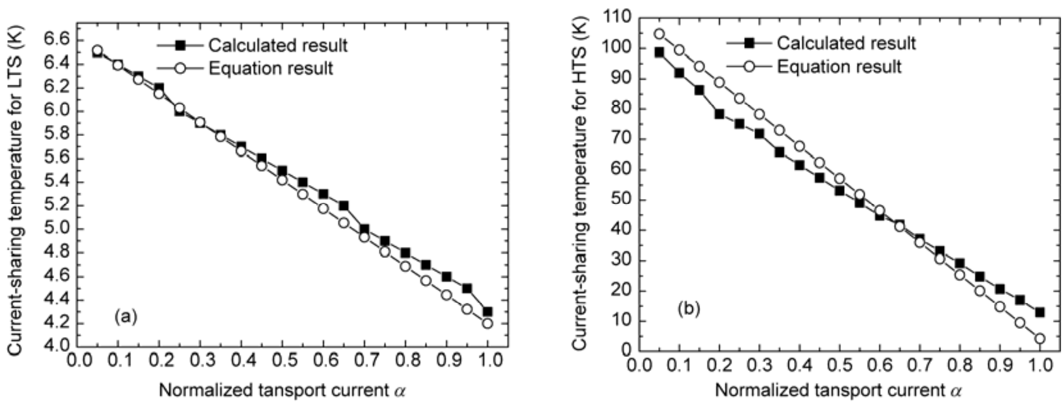

Figure 5 T_{CS} difference between the calculated result and the equation result for LTS (a) and HTS (b).

cooled by a cryogenic refrigerator without liquid helium usually have worse cryogenic stability than the system with the liquid helium. Therefore, a few K's increase of T_{CS} compared with typical LTS made us believe that this LTS/HTS hybrid conductor will be explored a new research field for the cryogenic stability of low temperature superconductors. Experiment of current-sharing temperature for LTS/HTS hybrid conductor will be undertaken in our future work.

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